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## MEMORANDUM

APPLICATION OF GAS ANALYSIS TO COMBUSTOR RESEARCH

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Cleveland, Ohio

NATIONAL AERONAUTICS AND  
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## APPLICATION OF GAS ANALYSIS TO COMBUSTOR RESEARCH

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### SUMMARY

The performance of turbine-engine combustors usually is given in terms of operating limits and combustion efficiency. The latter property is determined most often by measuring the increase in enthalpy across the combustor through the use of thermocouples. This investigation was conducted to determine the ability of gas-analytical techniques to provide additional information about combustor performance. Gas samples were taken at the outlet and two upstream stations and their compositions determined. In addition to over-all combustion efficiency, estimates of local fuel-air ratios, local combustion efficiencies, and heat-release rates can be made. Conclusions can be drawn concerning the causes of combustion inefficiency and may permit corrective design changes to be made more intelligently. The purpose of this investigation was not to present data for a given combustor but rather to show the types and value of additional information that can be gained from gas-analytical data.

### INTRODUCTION

The combustion efficiency of turbine-engine combustors is normally determined by measuring the increase in enthalpy across the combustor through the use of thermocouples. Olson and Bernardo have shown that this simple technique gives accuracies adequate for most purposes provided enough thermocouples are used at the combustor outlet to properly indicate average temperatures (ref. 1). However, as pointed out in Fiock's comments on the Olson paper (ref. 1, p. 333) the method is subject to criticism because, on a theoretical basis at least, thermocouples may not indicate true gas temperatures in the combustor environment.

Combustion efficiencies can be determined alternatively from the concentrations of unburned constituents in the exhaust gas (ref. 2). This technique has been used little in the United States but is used more widely in England and is highly recommended by Bragg and Holliday (ref. 3).

There are several disadvantages in this use of gas analysis. First, quantitative analysis for the various unburned components in exhaust-gas samples is obviously more difficult than taking simple temperature measurements. There are, however, systems that will continuously indicate or record exhaust-gas composition (ref. 3). Second, it is mechanically more cumbersome to take gas samples at many points across a combustor outlet than it is to use the same number of thermocouples. This factor of sampling density is important in accurately determining the mean values of exhaust-gas properties when there are large temperature or concentration gradients. Third, the gas analytical approach becomes more complicated if components having low volatility are present; these may condense and may not reach the analytical instruments unless transfer lines are heated. And finally, since the outlet temperature profile is an important consideration in combustor design, the direct measurement of temperature is often required in any case even though efficiencies are determined by other means.

However, as pointed out in reference 3, there are significant advantages in the use of gas analysis for determining the performance of combustors. First, at high combustion efficiencies (low inefficiencies), the gas analytical approach is inherently more accurate because inefficiency is measured directly and not as the difference between two large numbers. This latter factor occasionally results in combustion efficiencies greater than 100 percent when measured by thermocouples. Second, some understanding of the rate-limiting processes can be derived from a knowledge of the types of components remaining in the exhaust gas; inefficiency due to poor preparation of the fuel-air mixture or inadequate flame spreading will appear as unburned fuel in the gas while inefficiency due to premature quenching of the flame or insufficient reaction times will result in the presence of carbon monoxide and hydrogen. Third, gas analysis will permit efficiencies to be measured in streams at temperatures above the working limits of thermocouples. This becomes important in considering propulsion systems for very high flight speeds. And finally, gas analysis can also be applied to samples taken not only at the combustor outlet but also upstream in the combustor and so, can permit estimates to be made of local fuel-air ratios, efficiencies, and heat-release rates. This type of data cannot be determined from temperatures alone.

Consideration of these advantages led to a study of the use of gas analysis in combustor research. The work was done with a production-model turbojet combustor over a range of pressures, air velocities, and fuel-air ratios. Samples were taken at the combustor exit and at two stations upstream and were analyzed using simple though time-consuming techniques. From these data estimates were made of local fuel-air ratios, efficiencies, and heat-release rates and suggestions made about the rate-limiting processes in this particular combustor. The results presented

herein point out the types of information that can be obtained through the analysis of exhaust-gas samples.

#### APPARATUS AND PROCEDURE

A production-model, tubular, turbojet combustor was used. The flame tube had a maximum diameter of  $7\frac{1}{2}$  inches and was  $27\frac{1}{2}$  inches long. It was installed, as shown in figure 1, in its production housing between flanges in a conventional duct facility, which provided metered air at ambient temperature only; an altitude exhaust system permitted subatmospheric operation. Fuel was supplied by means of calibrated rotameters. The exhaust-gas temperatures were measured by an array of 32 bare-junction, Chromel-Alumel thermocouples distributed on an approximately equal-area basis at a station 6 inches downstream of the flame tube. An arithmetical average from these couples was used as the combustor-outlet temperature for calculations of combustion efficiency.

Gas samples were taken through the water-cooled rake shown in figure 1. This L-shaped rake swept back and forth over  $360^\circ$  at 18 cycles per minute. The three ports in the probe end each swept centers of annuli of equal area. The probe could be run at any station between the dome of the flame tube and the outlet thermocouple station. The data reported herein were taken at either  $3\frac{1}{2}$ ,  $15\frac{1}{2}$ , or  $31\frac{1}{2}$  inches downstream of the fuel injector, the last being 1 inch ahead of the outlet thermocouples.

A diaphragm pump was used to pump the gases into previously evacuated, 33-liter, stainless-steel containers, which were filled to no more than 10 pounds per square inch gage to ensure that no hydrocarbons would condense in the tanks. The pump was run at full capacity so that the sampling rate varied somewhat with combustor operating conditions. The gas-sampling velocities, that is, the velocities through the inlet ports of the probe, were between one-half and twice the local stream velocities for those samples taken at the combustor outlet and at the mid-combustor stations. The forward sampling station was in a region of strong reverse flow where local velocities have little meaning.

The gas samples were analyzed using several techniques. Oxygen and carbon dioxide were determined with a precision-type (mercury displacement) Orsat apparatus with results accurate to 0.2 percent by volume. The residual combustibles (hydrogen, carbon monoxide, and hydrocarbons) were determined by a combustion train system similar in principle to the National Gas Turbine Establishment method reported in reference 2. In the NGTE method, carbon monoxide and hydrogen are selectively oxidized over cupric oxide at  $300^\circ\text{C}$  and the hydrocarbons are oxidized over platinum at  $950^\circ\text{C}$ . The combustion products are adsorbed and weighed. A cold trap at  $-80^\circ\text{C}$  is used to keep the higher-molecular-weight components out

of the first oxidation stage; these are subsequently vaporized and burned over the platinum.

The differences between the NGTE method of reference 2 and the one used for this work were: (1) using smaller samples with semimicro weighing techniques, (2) using platinized silica gel at 150° C in place of the cupric oxide oxidizer, and (3) using a colder trap (-160° C attained with isopentane slush) to keep ethylene, acetylene, and propylene from getting into the first-stage oxidizer. These three components are sufficiently volatile to pass a -80° C trap and are oxidized, in part at least, over the platinized silica gel; high values for carbon monoxide and hydrogen result unless the colder trap is used. Preliminary work showed that, while aldehydes were present, neither aldehydes nor acids contributed significantly to combustion inefficiency and, therefore, these components were not determined. Accuracies of 0.02 to 0.05 percent by volume were obtained for carbon monoxide and hydrogen depending on the sample size that was used. The concentrations of hydrocarbons were not generally calculated on a volume percentage basis, but, instead were expressed in terms of chemical enthalpy per unit volume, that is, Btu per cubic foot of exhaust gas. The concentrations of hydrogen and carbon monoxide were also calculated in these terms. The repeatability (and presumably accuracy) in the determination of hydrocarbons ranged from 0.1 to 0.5 Btu per cubic foot depending on sample size and hydrocarbon content. The hydrocarbon fraction of some of the samples was further characterized by the use of infrared spectroscopy and gas chromatography on concentrates collected in liquid-nitrogen-cooled traps. Gas chromatography was also used to verify the carbon monoxide and hydrogen results obtained by combustion-train analysis.

Calculations of the exhaust-gas compositions were straightforward with but one exception in that water vapor, an important product of combustion, was not determined in any of the tests; the analysis for all other components was on a water-free basis. Therefore, the concentrations of water had to be calculated from stoichiometric relations, which was done by using a carbon-atom balance to estimate the concentrations of fuel in the reactants. Because the hydrogen-carbon ratio of the fuel was known, a hydrogen-atom balance and an estimate of the water content of the products could then be made.

The data presented herein are in terms of Btu per hour. The total fuel flow to the combustor, the unburned combustibles at any station, and the heat release at any station are conveniently treated in these terms. The fuel input is the product of the hourly rate (in lb/hr) and the lower heat of combustion (in Btu/lb). The residual enthalpy of combustion due to the several combustibles in the exhaust was calculated by multiplying the concentration of each (in Btu/cu ft) by the cubic feet of gas passing the probe per hour. The heat released is the difference between the fuel input and the remaining combustibles when all quantities are expressed in terms of Btu per hour.

It was assumed that the number of moles of water-free exhaust gas was exactly equal to the number of moles of combustor-inlet air. This is a good approximation for turbojet conditions, introducing errors of less than 2 percent in all cases.

## FUELS AND TEST CONDITIONS

Preliminary work with a JP-4 fuel having a final boiling point of 450° F indicated that condensation of the heavy ends of the fuel in sampling lines and containers would be troublesome. Therefore, the bulk of the work was done with a gasoline having a final boiling point of 280° F. With this fuel there appeared to be no condensation losses except for samples taken from the front of the combustor where the fuel-air ratio is very high. Some work was done with diisopropyl (2,3 dimethylbutane), which boils at 137° F. With this fuel the fuel-air ratios would have to exceed 1.0 before condensation could occur. Since, even for samples taken at the upstream station the highest local fuel-air ratios are of the order of 0.25, there is no possibility of condensation losses with diisopropyl.

Tests were run over a range of combustor-inlet conditions and fuel-air ratios. The combustor-inlet pressure was first held at 15 inches of mercury absolute and a series run at reference velocities of approximately 50, 75, and 100 feet per second. (The reference velocities were based on the density of the air at combustor-inlet conditions, on the air mass-flow rate, and on the maximum cross-sectional area of the combustor housing.) Reference velocity was then held near 75 feet per second and runs made at inlet pressures of 10, 15, and 20 inches of mercury absolute. For each combustor-inlet condition (five in all) tests were run at fuel-air ratios of approximately 0.010 and 0.016, and at a ratio of 0.026 whenever possible. Combustion was unstable when the highest fuel-air ratio was attempted at 10 inches of mercury absolute and 75 feet per second and at 15 inches of mercury absolute and 100 feet per second; no data were obtained at these two sets of conditions. Samples were taken at a total of 13 operating conditions and for most of these conditions samples were taken at the front, middle, and exit combustor stations.

## RESULTS AND DISCUSSION

The results for 44 runs are listed in table I, which shows the combustor operating conditions, combustion efficiencies as measured by uncorrected bare-junction thermocouples (ref. 1), heat contents and heat-release rates in Btu per hour, and the combustion efficiencies calculated from the gas-analytical results. Various facets of these data are discussed in the following sections.

Comparison of Combustion Efficiencies as Measured  
by Thermocouples and by Gas Analysis

This comparison of combustion efficiencies from the two measurements can be made for samples taken at the combustor outlet. Since the rake swept a plane just 1 inch ahead of the thermocouple station, the efficiencies should be the same. The results are listed in table II.

For 11 of the 13 test conditions, efficiencies by the two methods agree within 4 percent with an average difference of 1.5 percent. Agreements of this order are quite satisfactory and are within the approximate limits of reproducibility of the two methods. However, for the other two conditions, the efficiencies obtained from temperature-rise measurements were 9 to 13 percent lower than those indicated by gas analysis. Tests at substantially the same conditions (runs 9 to 11 and 35 to 38) simply confirm this disagreement, as shown in table II. While the level of efficiency changed during these repeat runs, decreasing for runs 35 to 38 by 7 to 9 percentage points, the differences in efficiencies obtained by the two methods remained about the same.

Combustion efficiencies indicated by thermocouples are markedly lower than those determined by gas analysis at the two conditions where, qualitatively at least, it might be expected that the thermocouples would give low readings for gas temperatures. These are the conditions of lowest reference velocity and highest temperature (highest fuel-air ratio) in runs 9 to 11 and for the conditions of lowest pressure in runs 35 to 38. Low velocity and low pressure would reduce the convective heat transfer from gas stream to thermocouple and high temperature would increase radiant-heat losses from the thermocouple (e.g., ref. 1). Therefore, it might be expected that, at these two conditions, the thermocouples were indicating too-low temperatures and efficiencies lower than actual. Quantitatively, however, the discrepancies for these two conditions appear too great to be attributed to thermocouple errors alone. For example, compare the large discrepancies for runs 9 to 11 (made at approximately 50 ft/sec and at a fuel-air ratio of 0.025 to 0.026) with the excellent agreement for the otherwise similar run, 23, where only reference velocity was changed (increased to 72 ft/sec). This change in velocity would not be expected to make such a marked change in the accuracy with which thermocouples indicate gas-stream temperatures.

It is also difficult to see how the gas-analytical method could be greatly in error. Sampling velocities were, as they should be, approximately the same as the stream velocities. Loss of combustibles from the gas samples through condensation would result in high apparent efficiencies; however, this is believed impossible with the highly volatile fuels that were used. A remote possibility is that the fuels were cracked and



polymerized to form nonvolatile tars, which would be lost to the gas samples but there is no indication that this was the case.

In general, combustion efficiencies determined by gas analysis and by bare-junction thermocouples usually agreed. However, when disagreement was found, there was no certain way to judge which method of determination was more nearly correct. However, data from another rig (shown later) indicate that at least in one case the gas-analytical method was more accurate than uncorrected bare-junction thermocouples and that more sophisticated temperature-measuring devices are required to obtain precise efficiency data.

#### Axial Air Distribution Along Flame Tube

The design of the air-entry-hole configuration for turbojet flame tubes is a difficult problem because no simple relation exists between hole configuration and the distribution of air entering along the liner. Rather, this relation is dependent on such factors as cross-flow velocities, pressure drop, liner geometry, and combustor temperature rise. Therefore, considerable effort, often using a large degree of empiricism, is required to tailor these liners.

The experimental measurement of these airflows is, by most techniques, very difficult; this is especially true during burning. However, the fraction of air entering upstream from any given station can be easily calculated from the fuel-air ratio of the gas taken at that station and the over-all fuel-air ratio; this fraction is equal to the over-all fuel-air ratio divided by the local fuel-air ratio. Data of this type are shown for the combustor midstation in figure 2 in which the fraction of air entering upstream of the station is plotted against combustor reference velocity for 10 tests made at 15 inches of mercury absolute. This fraction decreases with increasing reference velocity and, at a given over-all fuel-air ratio, the front of the combustor would run richer with increasing velocity.

In a similar manner it was found that approximately 0.10 fraction of the air entered upstream of the forward sampling station. However, no consistent trends were observed as reference velocities varied.

The results shown in figure 2 for the effect of reference velocity on air distribution are in qualitative agreement with those predicted from an analysis given in reference 4. Both the experimental data and the theoretical calculations show that increasing reference velocity will

decrease the fraction of the total airflow entering upstream of a given station. A quantitative comparison cannot be made since the analytical study was made for an idealized parallel-wall combustor with no air entering the dome, a quite different configuration from that used in the experimental work.

In general, it appears that the distribution of air entering along a combustor can be determined within 5 percent if fuels of sufficiently high volatility are used. This can be done either with combustion or in cold flow.

#### Local Heat-Release Rates and Concentration of Unburned Components

While both combustion-efficiency and air-entry-rate data can be determined by means other than gas analysis, this technique is unique in that it can supply information on the local combustion processes occurring in the flame tube. Table I lists the concentrations of the different combustibles in terms of heat contents and also the heat-release rates calculated for the three combustor stations. From these data some insight can be gathered as to the rate-controlling processes. To help visualize these processes, figure 3 has been plotted with combustible content and heat release in terms of Btu per hour as functions of probe position. Only one run was plotted where more than one run was made. The dashed upper line on each figure represents the fuel-flow rate (in Btu/hr), the area below the lower line represents the heat already released and the interline areas show the concentrations of the various combustibles at each station. Three separate runs (one at each station) were required for each part of figure 3; the small shifts in some of the fuel-flow curves indicate a run-to-run variation in fuel rates.

Heat release rates. - Inspection of figure 3 shows that the over-all fuel-air ratio has a marked effect on local heat-release rates. This is especially true for the combustor dome upstream of the forward sampling station. A comparison of figures 3(a), (b), and (c), all at the same pressure and velocity but at fuel-air ratios of 0.010, 0.016, and 0.025 to 0.026, respectively, shows that the heat released decreased from 3.0 to 1.4 to  $0.7 \times 10^5$  Btu per hour in the forward section of the combustor as the over-all fuel-air ratio was increased. A similar effect is found in comparing the data of figures 3(d) to (f), and of figures 3(g) and (h). This decrease in heat release is the result of the local fuel-air ratio becoming overly rich at the higher over-all fuel-air ratios. In the previous section it was shown that approximately 10 percent of the total airflow entered upstream of the forward sampling station. Therefore, the local fuel-air ratio is approximately 10 times the over-all ratio or about 0.10, 0.16, and 0.25 for the three runs (1, 4, and 7). These local fuel-air ratios are all above the stoichiometric ratio of 0.067 and the higher values are certainly too rich to burn vigorously.

Bragg has suggested (ref. 3) that higher heat-release rates can be obtained when varying over-all fuel-air ratio either by varying the primary air or by staging the fuel. The preceding data confirm the necessity of this if these higher rates are required. The benefits of using an independent control on the primary air is demonstrated in reference 5 in which optimum combustion efficiencies were obtained over a range of fuel-air ratios by this control.

Inspection of figures 3(a), (d), and (g) also shows that there was no measurable heat release in the last half of the combustor at the low (0.010) over-all fuel-air ratio. Significant quantities of combustibles still existed at the midstation in these tests and the lack of further conversion resulted in combustion inefficiencies probably because of the relatively low temperatures that the systems reached by midstation. These temperatures were estimated to average between  $1100^{\circ}$  and  $1300^{\circ}$  F for the three runs (2, 13, and 25). At these lean conditions the combustor could be shortened by one-half with no loss in efficiency; however, some of the extra length might still be required to control the outlet temperature profile.

On the other hand, there was a considerable heat release in the last half of the combustor at the higher fuel-air ratios. This is especially true at the richest conditions (figs. 3(c), (f), and (h)). For these conditions a longer combustor would give some increase in efficiency. The gain might not be as great as inspection of the figures suggests since these are three point curves connected by straight lines; additional data points might give curves that approach 100-percent efficiency asymptotically. The midstation average temperature was estimated to be  $2300^{\circ}$  to  $2400^{\circ}$  F for runs made at a fuel-air ratio of 0.025.

Rate-limiting processes. - One of the reasons for this study was to see if information on the rate-limiting processes could be obtained from the nature of the combustibles still present within the flame tube and at the combustor outlet. Two quite different types of processes might be involved: (1) the physical process of mixing fuel and air to make a combustible mixture or the physical process of spreading the flame through the reaction mixture, (2) the chemical or kinetic process of burning the mixture. If a combustor does not supply adequate atomization and vaporization of the fuel and adequate mixing of this fuel with air, then the residual combustibles largely should be the hydrocarbon fuel since pockets of fuel-rich and unreacted mixture should pass through the combustor. If the flame has not spread through the reactants before they pass the combustor outlet, the residual combustibles will again be hydrocarbons. Therefore, limitations of the physical mixing rates in either mixture preparation or flame spreading will result in gas samples that contain hydrocarbons as the unburned component. However, if the kinetics of the system is rate limiting the mixture will start to react, but, because of the limited stay time, will pass out of the combustor in only

partially reacted form. The system may also be prematurely quenched by the secondary air while in this partially reacted form. Data by Prescott et al (ref. 6) indicate the nature of the residual combustibles found when reaction is incomplete. In this investigation, gas samples were taken across the reaction zone of a fully premixed flame (propane-air Bunsen flame) and their composition determined by mass spectroscopy. Relatively large amounts of carbon monoxide and hydrogen and small amounts of ethylene and acetylene were found in the partially reacted gases. Carbon monoxide reached a maximum concentration of 7 percent and hydrogen a maximum concentration of 4 percent in the reaction zone. Therefore, in a combustor, a chemical rate-limited process should be revealed by the presence of carbon monoxide and hydrogen as the major combustibles. This is also the conclusion of reference 3.

The gas compositions plotted in figure 3 can be examined to see which, if either, of the two processes is rate-limiting over the range of operating conditions. The over-all observation is that substantial quantities of both carbon monoxide and hydrogen and also hydrocarbons were found in most samples, indicating that both physical and chemical factors were limiting the efficiency of the combustor.

However, for two of the conditions it appears that nearly all the inefficiency can be explained by a single rate-limiting step. One of these conditions is a combustor-inlet pressure of 15 inches of mercury absolute and velocity of 50 feet per second and at a fuel-air ratio of 0.010 (fig. 3(a)). At these lean conditions there was a vigorous reaction in the dome resulting in about one-half the potential enthalpy of the fuel being converted to heat ahead of the upstream sampling station. The residual combustibles at this point were approximately equally split between carbon monoxide plus hydrogen and hydrocarbon. Across the rest of the combustor length the carbon monoxide plus hydrogen was largely consumed but the hydrocarbons underwent little further reaction. The result was a substantial combustion inefficiency largely due to unburned hydrocarbons. These data indicate that the conversion rate was limited by inadequate mixing of fuel and air. It is likely that poor mixing was caused by poor atomization of the fuel since the atomizer was operating at a pressure drop of only 8 pounds per square inch.

When the fuel-air ratio was increased to 0.016 and other conditions held the same (fig. 3(b)), less heat was released in the dome but the concentration of hydrocarbons decreased to substantially zero at the combustor outlet. However, significant quantities of carbon monoxide remained unburned. In this case, the reaction rate was limiting the combustor efficiency although mixing of fuel and air was adequate. The pressure drop across the atomizer was 20 pounds per square inch and believed to be sufficient to give a good spray.

These two examples represent clear cases of one or the other of the two processes being rate limiting. For the rest of the conditions, the carbon monoxide plus hydrogen and the hydrocarbons were both present in significant quantities indicating that both the physical and the kinetic processes were important factors in the inefficiencies of the combustor.

These experimental results can be compared with the conclusions reached by Childs and Graves (ref. 7) through an analysis and correlation of the effects of combustor-inlet pressure, temperature, and velocity on combustion efficiency. Two combustors were studied (ref. 7) and, for one, the correlation indicated that only reaction kinetics was limiting performance over the range of conditions studied. The other combustor (combustor B of ref. 7) was the same model as that used in the work described herein. For this combustor it was shown that, depending on operating conditions, either physical or kinetic processes might be limiting performance. At high pressures the physical processes were rate-controlling and at low pressures the kinetic processes were most important. The crossover from one rate-limiting process to the other occurred at pressures of 10 to 20 inches of mercury absolute; that is, in this pressure range both processes were factors in combustion inefficiency. The experimental work reported herein was done over this same range of pressures. The conclusions reached through gas analysis partially confirm the analytical study of reference 7 in that both indicate that, over this range of pressures, both physical and kinetic processes are rate-limiting. An experimental study over a wider range of pressures would be desirable. Nevertheless, the experimental results do indicate that determinations of the types of residual combustibles may yield information that would be helpful in the design of combustors.

Nature of the hydrocarbon components. - In some unpublished data obtained previously from a different combustor with isooctane fuel, the fuel was found to be largely degraded to hydrocarbon fragments at an early stage in the combustion process. A sample was taken a short distance downstream of the injector in a very fuel-rich region and the hydrocarbon portion analyzed by infrared absorption spectroscopy. Only about 20 percent by weight of the hydrocarbon portion of the sample remained as unchanged isooctane. The remaining 80 percent was cracked fragments with large amounts of methane, ethene, acetylene, propene, and butenes present. This result indicated that the fuel was strongly heated in the fuel-rich environment and was extensively cracked prior to burning.

A similar analysis made of several samples in the present series showed quite different results. These samples were taken from the mid- and upstream stations during runs with diisopropyl fuel. The hydrocarbon portion was isolated by a freeze-out technique and the components determined by gas chromatography and infrared spectroscopy. Results are shown in table III in terms of percent by weight based on total hydrocarbon content. These data shown that the hydrocarbon portion of these gas

samples consisted of from 72 to  $9\frac{1}{2}$  percent original fuel, which indicates that the fuel portion of the remaining combustibles was not heated strongly enough to be cracked. These results are quite different from the earlier work and must reflect a difference in combustor design and in combustion processes between the two combustors.

Gas chromatography and the infrared spectra indicated that the two-carbon atom components were largely ethene and acetylene and that the three- and four-carbon atom components were largely propenes and butenes. The freeze-out technique employed here would not have trapped any methane that might have been present. However, a few supplementary tests indicated methane concentrations of less than 1C percent by weight of the hydrocarbon content.

#### Other Experimental Results

For several years prior to this program, gas samples occasionally were taken from other combustion systems. Turbojet and ramjet combustors were sampled and some of the results from these isolated experiments are discussed in this section. The examples cited are of particular interest because each gave new information for each combustion process.

In the first instance, an extensive development program resulted in an annular turbojet combustor with outstanding performance at low pressures (ref. 8). A sample taken from this combustor while operating at 5 inches mercury absolute with propane fuel gave the results listed in table IV. Here the combustion inefficiency is almost entirely due to carbon monoxide plus hydrogen and indicates that kinetic processes alone were limiting efficiency. This conclusion is in agreement with the analysis of reference 7, which predicts that chemical reaction should be rate-limiting at this very low pressure.

Incidental to this work, gas analysis indicated a combustion efficiency of 87 percent while, at the time of sampling, the uncorrected bare-wire thermocouple system indicated an efficiency of only approximately 70 percent. Subsequent refinements in the temperature-measuring system raised the indicated average outlet temperature to such a value that the efficiency by enthalpy rise agreed with that obtained by gas analysis.

Ramjet combustors were also studied. The ramjet is apt to be a somewhat less complicated system than the turbojet since the fuel is often injected into high-temperature air upstream of the flameholder. As a result the mixture preparation processes and combustion processes can be treated separately. The results from tests on two different combustors are given in table V. Ramjet A was run with an input fuel-air ratio equivalent to 100 Btu per cubic foot so that each Btu per cubic foot of combustible material in the exhaust gas was equivalent to a combustion

inefficiency of one percent. The B combustor was run slightly leaner (87 Btu/cu ft) so that 1.15 percent combustion inefficiency resulted from each Btu per cubic foot of combustible in the exhaust.

Ramjet A had a simple gutter-type flameholder and for this model about 80 percent of the inefficiency was due to residual hydrocarbon fuel in the exhaust gas. This clearly indicates that the cause of the inefficiency is insufficient flame spreading, which results from the use of a too-simple flameholding device. Ramjet B had a more efficient, can-type flame-holding system and was run at a more severe operating condition. For this combustor test, limitations in the kinetic rate process caused the inefficiency, as shown by the fact that most of the combustibles are carbon monoxide and hydrogen.

#### CONCLUDING REMARKS

The purpose of this paper is not to present in detail the findings from one particular combustion system but rather to use these findings to indicate the potential value of gas analysis as a research tool. It has been shown that gas analysis can be used with air-breathing systems to determine combustion efficiency and to confirm or question such data obtained by other means. In addition, it can be used to measure internal airflows and local heat-release rates. Gas analysis can also indicate rate-limiting mechanisms and may suggest hardware changes to overcome these limits.

In spite of these advantages, the gas-analysis technique has not seen wide usage, presumably because of the greater difficulty in determining chemical composition as compared with measuring other properties of a working fluid. While this is true for the results presented herein, it is not necessarily the case if sufficient instrumentation is applied to the problem. A system is shown in reference 3 in which three infrared gas analyzers, one paramagnetic oxygen meter, and one thermal conductivity cell are used to indicate continuously all the concentrations that are needed to get the type of data presented herein. It is probable that these instrument outputs could be fed to a computer system to give a direct indication of the several indices of combustor performance. Other analytical techniques, mass spectroscopy for example, could be used. In any case rapid response and continuous recording of combustor performance is possible if sufficient instrumentation is applied.

The proper sampling of the subsonic streams that are found in the turbojet environment is not too difficult. The greatest problem is the need for keeping all components in the vapor phase and to avoid the condensation of components having low volatility. This requirement made it necessary to use gasoline and, in some cases, diisopropyl in the present investigation rather than jet fuel. However, a steam-cooled probe and

steam-jacketed transfer lines might be used provided that analytical instrumentation could be installed near the combustor. The steam temperature would be both cool enough to quench hydrocarbon-air reactions and hot enough to keep the heavy components of most jet fuels in the vapor phase.

Lewis Research Center

National Aeronautics and Space Administration

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TABLE I. - SUMMARY OF COMBUSTOR TESTS

Run number	Pressure, in. Hg abs	Air reference velocity, ft/sec	Fuel	Fuel rate, Btu/hr	Over-all fuel-air ratio	Probe station (b)	Combustion efficiency by temperature rise, percent	Remaining combustibles Btu/hr			Heat released, Btu/hr	Combustion efficiency by gas analysis, percent
								H <sub>2</sub>	CO	Hydrocarbon		
1	15	50.8	G	6.18x10 <sup>5</sup>	0.010	F		0.43x10 <sup>5</sup>	1.08x10 <sup>5</sup>	1.66x10 <sup>5</sup>	3.0x10 <sup>5</sup>	
2	↑	51.8	G	↑	↑	E	83	.41	.23	.89	4.7	82
3	↑	51.3	G	↑	↑			.01			5.1	
4	15	50.8	G	10.1	.016	F		.38	.84	7.50	1.4	
5	↑	51.2	G	↑	↑	E	93	.16	1.23	.58	8.1	93
6	↑	51.5	G	↑	↑			.09	.53	.09	9.4	
7	15	50.7	G	16.0	.026	F		.11	.31	14.90	0.7	
8	↑	49.3	G	16.1	↑	M		.95	3.05	3.11	9.0	
9	↑	50.4	G	16.1	.025	E	78	.12	.84	.50	14.6	91
10	↑	53.6	G	16.1	.028	E	79	.20	1.00	.81	14.1	88
11	↑	50.6	D	16.6		E	77	.23	.99	1.03	14.4	86
12	15	80.5	G	9.88	.010	F		.56	1.67	4.10	3.6	
13	↑	74.5	G	9.85	.011	M		.05	.55	.48	8.8	
14	↑	75.0	G	9.85	.010	E	85	.11	.53	.69	8.5	86
15	15	77.1	G	15.7	.016	F		.42	.98	12.40	1.9	
16	↑	77.3	D	↑	.017	P		.66	.82	13.40	0.8	
17	↑	73.3	G	↑	↑	M		.43	1.79	1.35	12.1	
18	↑	73.2	D	↑	↑	M		.84	2.05	2.34	10.5	
19	↑	75.0	G	↑	.016	E	82	.19	1.43	.85	13.2	84
20	15	76.0	G	22.2	.024	F		1.00	.21	21.20	0.8	
21	↑	73.3	G	24.4	.027	M		.92	2.62	8.55	12.3	
22	↑	74.5	D	24.7	↑	M	75	1.36	2.92	4.31	16.1	74
23	↑	72.0	G	24.4	↑	E		.45	2.50	3.46	18.0	
24	15	100.0	G	13.1	.011	F		.28	.83	8.60	3.4	
25	↑	101.2	G	↑	.011	M		.07	.86	.48	11.7	
26	↑	99.4	G	↑	.010	E	86	.15	.87	.41	11.7	89
27	15	100.0	G	18.9	.016	F		.16	.91	16.00	1.8	
28	↑	98.5	G	18.9	↑	M		.79	2.42	2.26	13.4	
29	↑	99.4	G	19.8	↑	E	77	.40	2.04	1.29	16.1	81
30	10	78.2	D	6.86	.011	M		.23	.59	.53	5.5	
31	↑	78.4	G	6.33	.010	E	65	.20	.57	1.47	4.1	63
32	↑	75.5	D	6.98	.011	E	77	.34	.44	.59	5.6	80
33	10	75.5	D	10.9	.018	F		.12	.61	9.00	1.2	
34	↑	76.6	D	10.9	.017	M		.62	1.57	2.82	5.9	
35	↑	76.0	G	10.1	.016	E	76	.13	.99	.27	8.7	86
36	↑	80.0	G	10.1	.016	E	74	.13	1.04	.47	8.5	84
37	↑	72.7	D	11.0	.018	E	69	.33	1.12	.65	8.9	81
38	↑	71.7	D	10.9	.018	E	67	.32	1.09	.86	8.6	79
39	20	76.0	G	13.1	.011	E	92	.26	.55	.28	12.0	92
40	20	75.6	D	19.1	.015	F		1.24	1.28	15.10	1.5	
41	↑	77.0	D	19.1	↑	M		.89	2.18	1.59	14.4	
42	↑	74.0	G	20.9	↑	E	92	.13	1.27	.58	18.9	91
43	↑	77.7	G	18.9	↑	E	87	.58	1.28	.62	16.6	88
44	20	76.3	D	28.6	.023	E	78	1.01	2.62	2.13	22.8	80

a Gasoline fuel, G; diisopropyl fuel, D.

b Sampling at front, F; sampling at middle, M; sampling at exit, E.

TABLE II. - COMPARISON OF COMBUSTION EFFICIENCY  
DETERMINED BY TWO METHODS

Run number	Operating conditions				Combustion efficiency, percent, as determined by -		Difference between efficiency determinations
	Pressure, in. Hg abs	Reference velocity, ft/sec	Fuel (a)	Fuel-air ratio	Gas analysis	Thermocouples	
3	15	51	G	0.010	82	83	-1
6	15	52	G	0.016	93	93	0
9	15	50	G	0.026	91	78	+13
10	↓	54	G	.025	88	79	+9
11	↓	51	D	.026	86	77	+9
14	15	75	G	0.010	86	85	+1
19	15	75	G	0.016	84	82	+2
23	15	72	G	0.027	74	75	-1
26	15	99	G	0.010	89	86	+3
29	15	99	G	0.016	81	77	+4
31	10	79	G	0.010	63	65	-2
32	10	76	D	.011	80	77	+3
35	10	76	G	0.016	36	76	+10
36	↓	80	G	.016	34	74	+10
37	↓	73	D	.018	31	69	+12
38	↓	72	D	.018	79	67	+12
39	20	76	G	0.011	92	92	0
42	20	74	G	0.015	91	92	-1
43	20	78	G	.015	88	87	+1
44	20	76	D	0.023	80	78	+2

<sup>a</sup>Gasoline fuel, G; diisopropyl fuel, D.

TABLE III. - ANALYSIS OF HYDRO-  
CARBON PORTION OF COMBUSTIBLES

Run num- ber	Combustibles, percent by weight				
	Hydrocarbons				
	Diiso- propyl	C <sub>5</sub>	C <sub>4</sub>	C <sub>3</sub>	C <sub>2</sub>
16	$97\frac{1}{2}$	$\frac{1}{2}$	--	1	1
18	84	$2\frac{1}{2}$	$\frac{1}{2}$	5	8
22	$93\frac{1}{2}$	$1\frac{1}{2}$	$\frac{1}{2}$	2	$2\frac{1}{2}$
33	89	--	$1\frac{1}{2}$	$4\frac{1}{2}$	5
34	78	$\frac{1}{2}$	$\frac{1}{2}$	7	14
40	86	$\frac{1}{2}$	$1\frac{1}{2}$	5	7
41	72	2	1	$5\frac{1}{2}$	$19\frac{1}{2}$

TABLE IV. - COMBUSTIBLES IN EXHAUST OF  
EXPERIMENTAL TURBOJET COMBUSTOR

Component	Combustible content, Btu/cu ft	Equivalent combustion inefficiency, percent
Carbon monoxide	3.48	11.2
Hydrogen	.52	1.7
Hydro- carbon	.05	.2
TOTAL		<u>13.1</u>
Combustion efficiency, percent		86.9

TABLE V. - COMBUSTIBLES IN RAMJET EXHAUSTS

Component	Ramjet A		Ramjet B	
	Combustible content, Btu/cu ft	Equivalent inefficiency, percent	Combustible content, Btu/cu ft	Equivalent inefficiency, percent
Carbon monoxide	5.0	5.0	7.0	8.0
Hydrogen	1.8	1.8	1.8	2.1
Hydro- carbon	30.0	30.0	2.0	2.3
TOTAL		<u>36.8</u>		<u>12.4</u>
Combustion efficiency, percent			87.6	
		63.2		

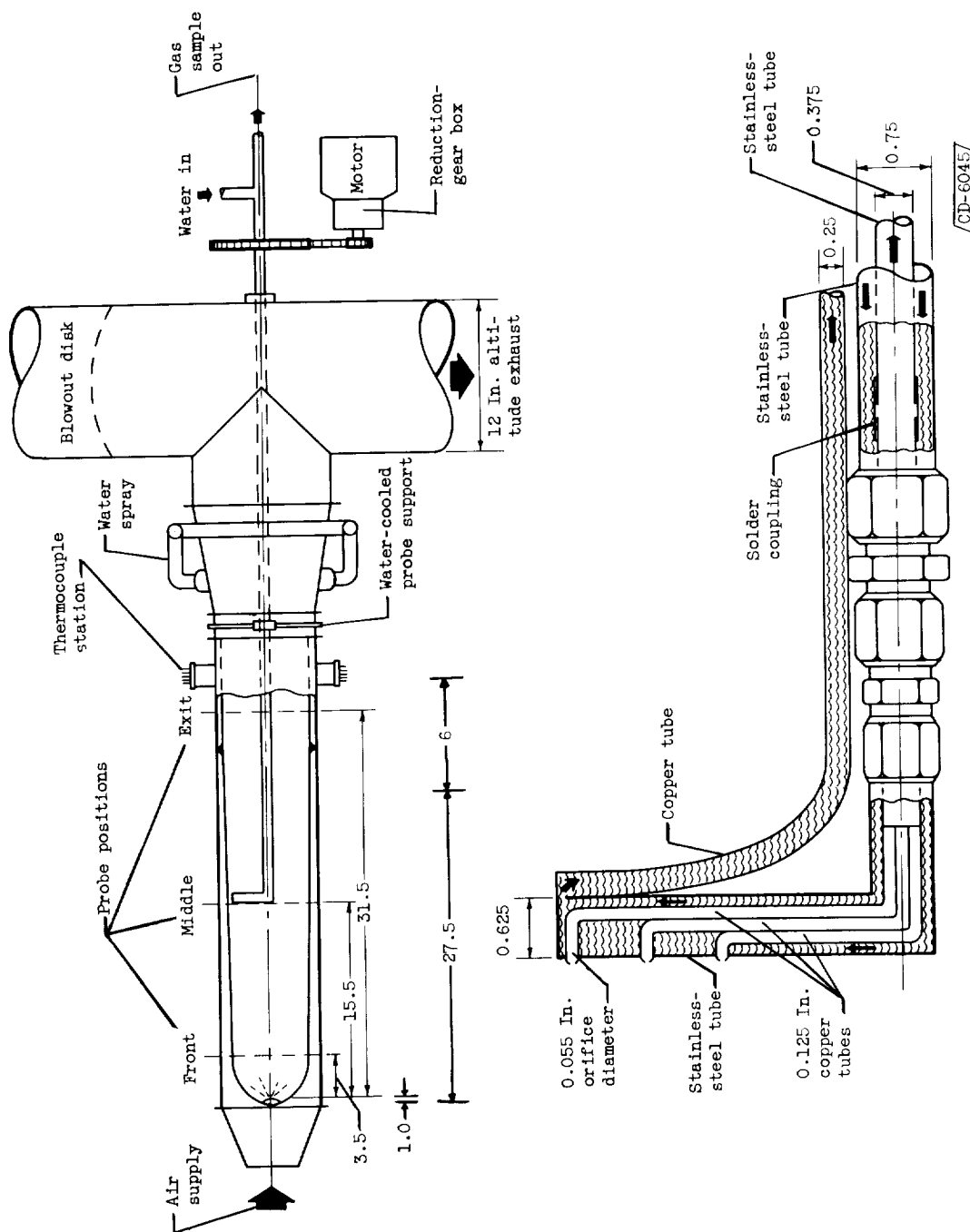


Figure 1. - Combustor test installation and sampling probe. (Dimensions in inches.)

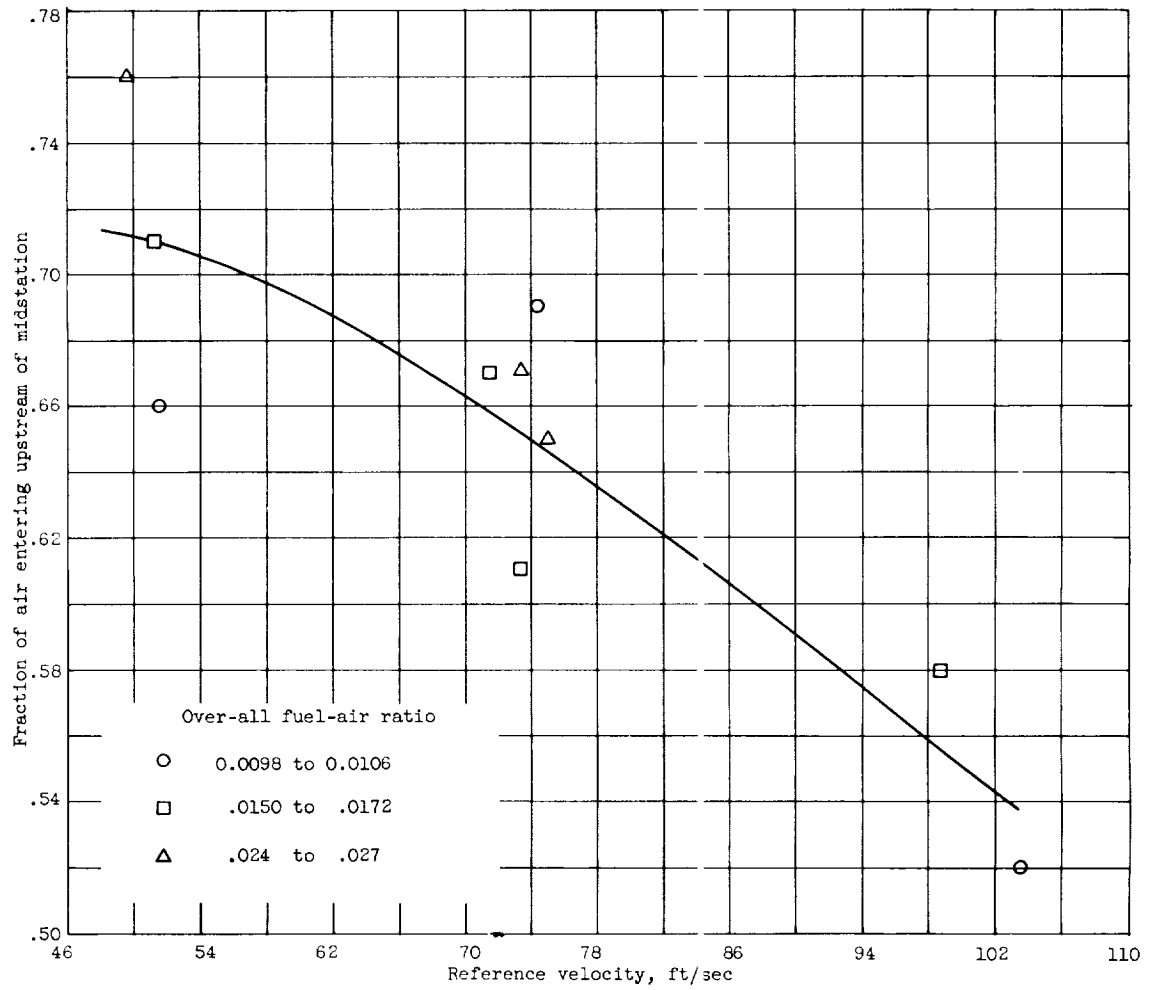
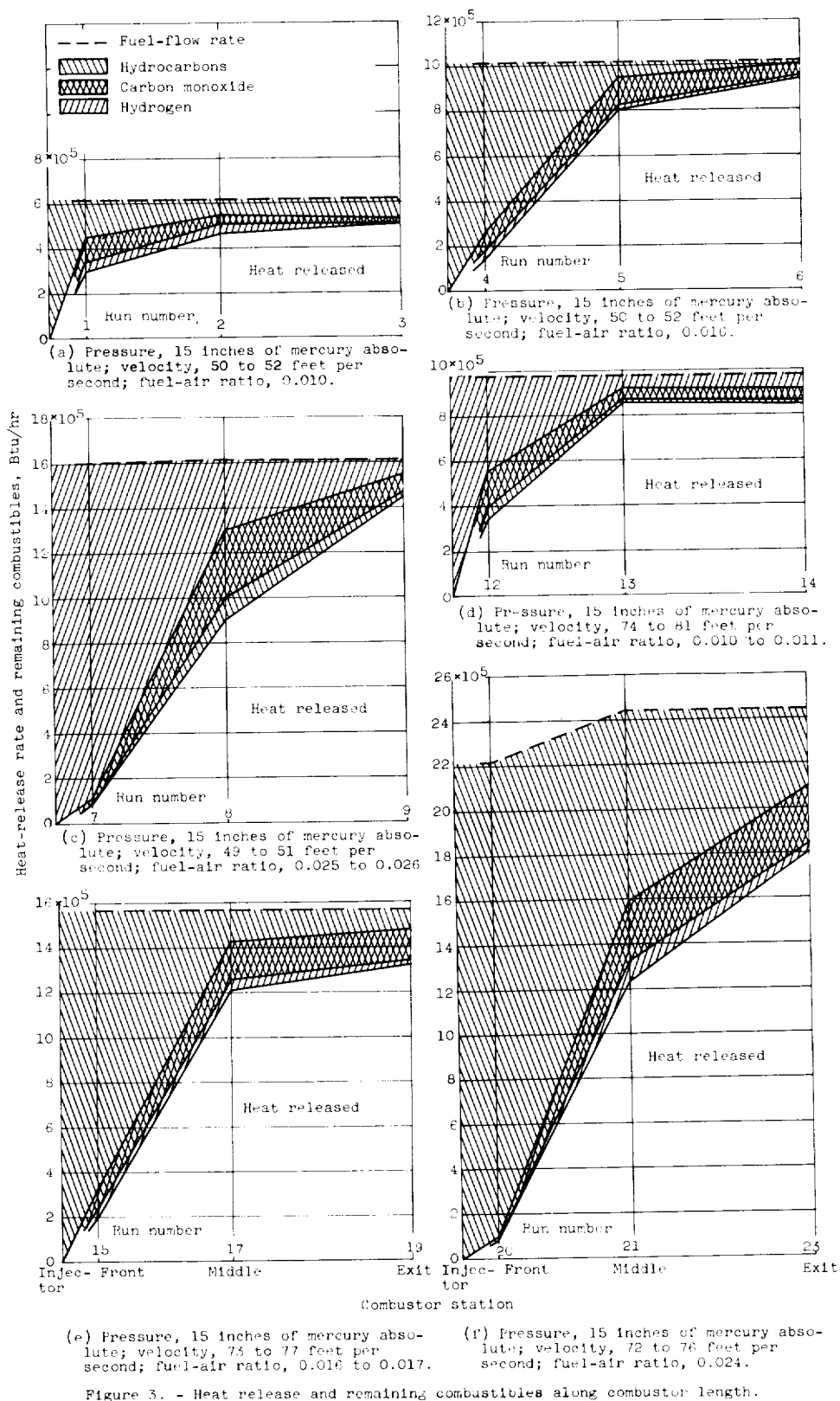


Figure 2. - Air distribution calculated from local fuel-air ratios. Pressure, 15 inches of mercury absolute.



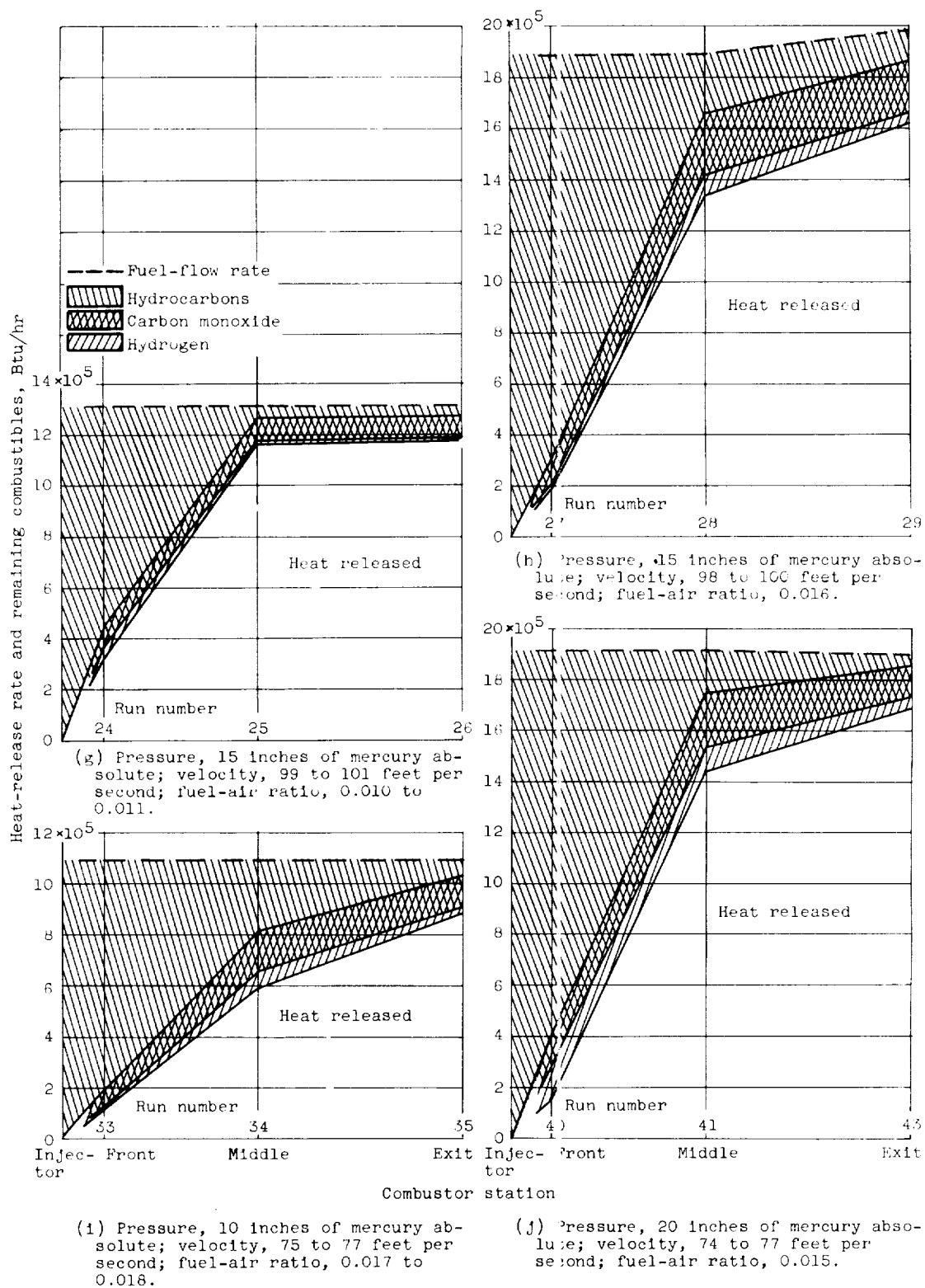


Figure 3. - Concluded. Heat release and remaining combustibles along combustor length.